DESIGN AND TEST OF AN ELECTRIC FURNACE PYROMETER

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I N T R O D U C T I O N

According to latest estimates (1920), almost a billion dollars worth of coal is wasted every year in the United States due to inefficient combustion of fuels under steam boilers. The average boiler efficiency is around 50% and could be easily raised to around 70% if the biggest loss due to imperfect combustion could be eliminated.

The problem then resolves itself into finding a method for determining the proper proportioning of air and fuel in the furnace. This method must be simple enough for the fireman to follow, and the more independent the device used, as a guide is of local conditions the more its practicability.

Now, if the temperature of the furnace, or rather of the gases leaving the furnace,be studied, it will be found that the closer the amount of air used for combustion is to theoretical requirements the higher will the furnace temperature be. In fact, as will be shown later, for all fuels satisfying the condition that they require 7.5 lbs. of air or thereabouts for each 10,000 Btu. of their heat value, there is a definite maximum temperature for the gases in the furnace for perfect combustion. If 200% air

is used, the temperature of the furnace will be about half its maximum, and, in general, the temperature will be practically inversely proportional to the relative amount of air used.

The furnace temperature is, therefore, a guide to combustion efficiency. Thus suppose that it is desired to avoid clinker formation and the burning out of arches, so that a furnace temperature of 2000 ^{o}F is decided upon as the ideal one. Then, if for the fuel used, the maximum theoretical temperature is 4000 ^{o}F, the chosen temperature corresponds to about 200% air or to a 100% excess. If 7.5 lbs. of air is the theoretical requirement for 10,000 Btu., and if the boiler room and flue gas temperatures are, say, $80^{o}F$ and $480^{o}F$, respectively, the loss due to excess air, for an average specific heat of .25, is,

$$\text{Excess Air losses} = .25\ (7.5+1)(480 - 80) =$$

$$= 850 \text{ Btu.}$$

or

$$100\ \frac{850}{1000} = 8.5\%$$

For 200% air, the loss is doubled and is, therefore, increased to 17%. Considering the fact that the usual excess air found in practice is around 300-400%, the losses due to excess air are reduced from

32 or 42.5% to only 17%,

with a resulting saving of about 20%, if the furnace

temperature is maintained at $2000^{o}F$ by damper regulation with a furnace pyro-meter as a guide.

A simple reliable furnace pyrometer would, therefore, make possible tremendous fuel savings, if followed by the fireman. The difficulties of using thermo-couple pyrometers for measuring furnace temperatures are twofold. In the first place the temperatures of the gases in the furnace vary by several hundred degrees from point to point, so that the indications of one thermo-couple in a furnace of say 100 square feet of grate, surface would be meaningless on account of such poor "sampling efficiency".

In the second place, the average thermo-couples are not suited for continuous exposures to temperatures ranging from 2000 to $3500^{o}F$.

Optical pyrometers are not satisfactory chiefly because they indicate the temperature of the fuel bed instead of the gas temperature. In fact a variation of about $800^{o}F$ in the gas temperature has been found to correspond to only a small change of about $200^{o}F$ in the fuel bed temperature.

For this reason a new electric furnace pyrometer has been devised of a high "sampling efficiency" and of great sensitivity and simplicity. This thesis comprises a discussion of the theory design and test of this type of furnace pyrometer which was installed on a 350 H.P. Stirling Boiler at the Armour Institute steam power plant.

GENERAL DESCRIPTION AND THEORY

In practically every furnace, the hot gases pass over the bridge wall before reaching the boiler tubes or the flues, as the case may be. The average temperature of the gases as they pass over the bridge wall is, therefore, the one that would indicate the combustion efficiency of the furnace.

Suppose now that a conducting, say metal, tube is passed through the setting above the full length of the bridge wall and water is allowed to flow continuously through this tube at a constant rate. Then the rise in the temperature of the water due to the effect of the hot gases on the tube is evidently an indication of the average temperature of the hot gases along the full length of the bridge wall.

The test pyrometer used on the Sterling Boiler consisted of 3/4" wrought iron pipe stretched across the bridge wall and supported by a 24" wall on one side and by about a 36" wall on the other side. It was connected to a city water main, and discharged into the sewer, the flow being regulated by means of a valve.

The design of such a pyrometer involves two distinct phases.

(1) The thickness, diameter, length and material of the tube must be such that the final water temperature for the highest furnace temperature to be measured

shall be safely below boiling points. The rise of the water temperature should be between 25 and 100°F. to be conveniently measured, and the heat absorbed by the pyrometer tube should be as small as possible, or only a fraction of a percent of the boiler rating. The coefficient of heat transmission should bear a definite constant relation to the temperatures measured.

(2) The thermal e.m.f., if thermo-couples are used, should be sufficient to make it possible to use a comparatively rugged millivoltmeter. If a recording pyrometer is desired, means must be found to measure something which can be recorded, e.g., resistance.

The problem then is both a mechanical and electrical one.

Analyzing the problem of heat transmission first, we have the relation;

(1) $US\ (tg - tw) =$ Heat absorbed by tube,

and

(2) $60\ WC\ (t_2 - t_1) =$ Heat given up to water,

where

$U =$ Coeff. of heat transmission $\dfrac{\text{Btu.}}{\text{Hr.xSq.Ft.x}^{\circ}\text{F.}}$

$S =$ Tube Surface, Sq. Ft.

$tg =$ Temperature of gases in furnace

$tw =$ Mean temper. of water in tubes

t_2 = Temper of water, hot end

t_1 = " " " , cold end

W = Water discharge, LBS./M I N

C = Specific heat of water = 1

Since there are practically no losses, we have,

(3) $US\ (tg-tw) = 60\ W\ (t_2-t_1)$

For an average value of U = 20, as commonly used for boiler tubes, and for the pyrometer tube furnace temperature, etc. as used on the Stirling boiler, we have, U = 20,

$$S = \pi dl;\ d = 1''\ (O.D.);\ L = 9'3'' = 9.25'$$

or

$$S = \frac{9.25\pi}{12} = 2.42 \text{ sq. ft.}$$

$$tg = 2000^{\circ}F.$$

$$tw = 100^{\circ}F.$$

$$W = 60\ av\ D;\ a = .533 \text{ sq. in.}$$

$$V = 1.5 \text{ ft/sec. } D = 62\ \#/\text{cu.ft.}$$

or

$$W = \frac{60 \times .533 \times 1.5 \times 62}{144} = 20.7 \text{ lbs/min}$$

Therefore, the rise in water temperature is,

$$T_2-t_1 = \frac{US\ (tg-tw)}{60W} = \frac{20x2.42x1900}{60x20.7} = 74^{\circ}F.$$

The water is, therefore, safely below boiling point for the case considered. If the furnace temperature is much higher than 2000°F. the water rise may be still kept down by increasing the flow. Thus, if the

velocity is increased from 1.5 to say 3 ft./sec. the temperature of the furnace could be in the neighborhood of $3900^{o}F$. for the same water temperature rise of $74^{o}F$.

It is also evident that the above water temperature rise is large enough for electrical measurement. However, if we analyze the assumed design for heat absorbed, we find that,

$$\text{Heat absorbed} = US\ (tg - tw) = 20 \times 2.42 \times 1900 =$$

$$92{,}000 \text{ Btu/Hr} = \frac{92{,}000}{33{,}500} =$$

2.75 Boiler Horse Power.

or

$$100\ \frac{2.75}{350} = .785\%$$ Boiler rating which is unnecessarily too large.

By proper choice of the material and the dimensions of the pyrometer tube, the heat absorbed may be considerably reduced without appreciably affecting the water temperature rise or the sensitivity of the pyrometer. For, rewriting (3) we get,

$$U\ dl\ (tg-tw) = 3600\ avD\ (t_2-t_1) =$$

$$3600\ \frac{\pi (Kd)^2}{4 \times 144}\ 62v\ (t_2 t_1)$$

or

$$VL\ (tg-tw) = 387k^2 d\ v\ (t_2-t_1),$$

where K is the ratio of $\frac{\text{inside diameter}}{\text{outside diameter}}$

(4) From the last equation we note that if U is decreased we must only decrease either K^2d, or v in proportion, to still retain the same water tempera-

ture rise, $t_2 - t_1$.

Now, sensitivity may be considered as the time it takes for a change in furnace temperature to be recorded by the pyrometer. For a given lag of heat transmission through the pyrometer tube, the time considered, must evidently depend upon the time it takes for the water to pass through the full length of the tube. Therefore, the greater the velocity of flow, the shorter this time is and the greater the sensitivity. Therefore, to reduce the heat absorbed without affecting either sensitivity or rise of water temperature, the proper method is to decrease the coefficient of heat transmission U, and the diameter, d, of the pyrometer tube or the expression, $K^2 d$ in equal proportion.

It may be remarked, in passing that for the pyrometer tube under discussion, the time it takes for a particle of water to move from the cold to the hot end is,

$$t = \frac{l}{v} = \frac{9.25}{1.5} = 6.16 \text{ sec.}$$

If a change of furnace temperature occurs at the hot end of the pyrometer tube the time it takes for the effect to be recorded is zero. The mean time for the recording of furnace temperature changes at any point of the tube must therefore, be,

$$t_a = \frac{6.16+0}{2} = 3.08 \text{ sec.}$$

Hence the gratifying sensitivity of this type of furnace pyrometer.

Before redesigning the tube, let us rewrite equation 1 and 4 in terms of internal diameter d_i, of the tube, and thickness, $T = nd_i$ Thus,

$$(5)\quad d = d_i + T = d_i(1+n),$$

$$(1_a)\quad US(t_g - t_w) = V\pi dl\ (t_g - t_w) = U\pi d_i(1+n)L\ (t_g - t_w) = \text{Heat absorbed},$$

$$(4_a)\quad UL(t_g - t_w) = 387\ \frac{d_i^2}{d}\ v(t_2 - t_1) = 387\ \frac{d_i}{1+n}\ v\ (t_2 - t_1)$$

Suppose, now, that the inside diameter, d_i, is reduced from $\frac{3}{4}$" to $\frac{1}{4}$", and U is decreased in proportion, or to 1/3 its original value. Then there will be no change in either sensitivity or water temperature rise , but there will be a large reduction in heat absorbed, since in eq. (1_a) reduced to 1/3 their former value. The reduction is therefore to 1/9 of the former heat absorbed, and we have,

$$\text{Heat absorbed} = 1/9\ (92{,}000) = \underline{10{,}200\ \text{Btu/hr}} = \frac{10{,}200}{33{,}500} =$$

$$= .3\ \underline{\text{Boiler Horse Power}}$$

The value of U can be reduced by increasing the thickness of the pyrometer tubes and by choosing a material which is a cross between a good heat conductor and an insulator. It is thought that alundum, the earthen material, which has lately come into use for protecting pyrometer thermocouples, is such a material, inasmuch as it certainly has a much smaller heat conductivity than metal, but still has not so much heat $\frac{\text{transmission}}{\text{log}}$ as to be unsuited for pyrometry.

The experimental investigation of the furnace pyrometer under discussion was planned along the following lines:

(1) The relation between furnace temperature distribution and the furnace pyrometer was to be investigated for different temperature ranges. The coefficient of heat transmission, U, was to be found for different furnace temperatures, with the velocity of the water in the pyrometer tubes being kept constant. The effect , if any, of tooth or fused ash accumulations of the pyrometer tube on the coefficient of heat transmission, V was to be found; also, the variation, if any, of v, with the velocity of the water in the pyrometer tube.

(2) The relation between heat transmission, from a hot gas to water through a tube, and the thickness of the tube was to be sought. Seamless steel and alundum tubes were to be experimented with.

Because of the great time consuming nature of investigating furnace temperature distribution, all readings were taken only for a constant water velocity of about, 1.5 ft/sec. Preparations were made for part (2) of the test, but the electric furnace used could not produce a temperature of 2000° F. as was planned. It was calculated that it would be necessary to almost double the platinum ribbon winding of the furnace in order to consume the full 3KW. of the furnace rating, since the current was limited to 30 amperes. Various factors made this plan unattainable within the period available for the investigation, and the latter had to postponed for a future time.

However, the method of analyzing the effect of tube thickness onthe coefficient of heat transmission is given below, the derivations of the basic relations being given in the appendix.

Before taking this matter up, it is interesting to note what the effect according to eq.(4a) and (1a) would be if the thickness of tube were varied for a given internal diameter d_i. Thus, if the thickness were increased, and therefore also $e^{\frac{i}{1+n}}$, then according to

eq. (1_a), V would have to be proportionately decreased in order that the heat absorbed should not increase also. Increasing of thickness would decrease U but in all probably much less than in proportion to $1+n$. Therefore, for a given material with a fixed internal diameter, increase of thickness would probably also increase the heat absorbed by the tube. If the changes of $1+n$ and U were universely proportional to each other, then according to eq. (4_a) the water themperature rise would not be affected thereby. But neither would the heat absorbed be decreased. Therefore, at the best there would be no gain. In fact since, in all probability, the coeffieient, U would be decreased but slightly in comparison with the effect of increase of thickness upon the increase of $1+n$, the net result would be an increasein water temperature rise, t_2-t_1. Although the latter is in itself desirable, it is not so at the expense of increase in heat absorbed. However, just what relation does increase in thickness bear to decrease in V is something to be found yet.

It is shown in the appendix that if, t_g=mean temperature of the gas, t_{mo}=mean temperature of tube, outside

t_{mi}= " " " " , inside

t_m = " " " ", at any thickness, T, from inside surface.

t_1=temperature of water, cold end

t_2= " " " , hot "

t = " " " , at distance, L, from cold end.

d_x=diameter of any point inside the metal

V_1=coefficient of heat transmission, from gas to metal

V_2= " " " " " metal to liquid

C =Metal conductivity,

that the fact that as much heat is transmitted from the gas to the

eq. (15), I would have to be proportionally increased in order that the heat absorbed should not increase also. Increasing of thickness would decrease U but it is not probably much less than in proportion to $\frac{1}{d}$. Therefore, for a given tube with a given internal diameter, increase of thickness would probably also increase the heat absorbed by the tube. If the changes of l_m and q were inversely proportional to each other, then according to eq. (15) it would [illegible] rise would not be affected thereby. [illegible] would the heat absorbed be increased. Therefore, at the best there would be no gain. In that case, in all probability, the coefficient, I would be decreased but slightly in comparison with the effect of increase of thickness upon the increase of l_m, the net result would be an increase in water temperature rise, t_2-t_1, although the latter is in itself desirable. It is not so at the expense of increase in heat absorbed. However, just what relation does increase in thickness bear to increase in V is something to be [illegible].

It is [illegible] in the apparatus that if, t_m = mean temperature of the gas, t_{mo} = mean temperature of tube, outside

t_{mi} = " " " , inside

t_x = " " " , at any thickness x, from inside surface.

t_1 = temperature of water, cold end

t_2 = " " " , hot "

t = " " " , at distance, x, from cold end.

l_m = diameter of [illegible] inside the tube

V_1 = coefficient of heat transmission, from gas to metal

V_2 = " " " " , metal to liquid

C = metal conductivity,

and the fact that as much heat is transmitted from the gas to the

metal as through the metal as well as from the metal to the water can be expressed by the following three equations:

$$(6)\ V\pi d(t_g - t_{mo}) = C\pi d_x \frac{\partial t_m}{\partial d_x}$$

$$(7)\ C\pi d_x \frac{t_m}{d_x} = V_2\pi k\, d(t_{mi} - t)$$

$$(8)\ V_2\pi K\ d\ (t_{mi} - t) = \frac{w\pi K^2 d^2}{4}\ v \frac{\partial t}{\partial l}$$

Since the heat transmitted through any given cylindrical layer of metal must be the same as that passing through any other layer, this heat must be independent of the cylindrical alyer diameter, d_x, and must be a function of l only; i. e.,

$$(9)\ C\pi d_x \frac{\partial t_m}{\partial dx} = f(l)$$

With the help of the last equation, the preceding three can be modified, as shown in the appendix, to the follwoing forms:

$$(6a)\ A_1\ (t_g - t_{mo}) = A_2\ (t_{mo} - t_{mi})$$

$$(7a)\ A_2\ (t_{mo} - t_{mi}) = A_3\ (t_{mi} - t)$$

$$(8a)\ A_3\ (t_{mi} - t) = f\ (L)$$

where,

$$A_1 = V_1\pi d$$

$$A_2 = \frac{C\pi}{\log_e \frac{1}{k}}$$

$$A_3 = V_2\pi kd$$

$$f(L) = \frac{w\pi k^2 d^2}{4} v \frac{\partial t}{\partial L}$$

If for direct comparison between the gas temperature, t_g, and the water temperature, t, the common form fo the heat transmission equation, were used, we should have,

$$(10)\ V\pi d\ (t_g - t) = f(L), \text{ or}$$

$$(10a)\ A\ (t_g - t) = f(L)$$

where,

$A = V_{\pi}d$

The relation between this "resultant" coefficient, V, and the "component" coefficients,

V_1, V_2, C, is shown to be,

(11) $\frac{1}{A} = \frac{1}{A}, \quad \frac{1}{A_2} \quad \frac{1}{A_3},$

or similar to the expression for electrical resistances in series.
Since V, V_1, V_2, and C increase with "heat conductance", their reciprocals, and therefore also, $\frac{1}{A}, \frac{1}{A_1}, \frac{1}{A_2}, \frac{1}{A_3}$ represent what many be called "heat resistances". There is thus an analogy between the expressions for electrical resistances and for heat resistances in series, which is rather striking.

Rewriting equation (11) with proper substitutions, we get,

(12) $$\frac{1}{V\pi d} = \frac{1}{V_1 \pi d} \quad \frac{\log_e \frac{1}{K}}{C\pi} \quad \frac{1}{V_2 \pi kd}$$

or

(12a) $$\frac{1}{V} = \frac{1}{V_1} + \frac{d\log \frac{1}{k}}{C} \quad \frac{1}{KV}$$

Since,

$d_i = kd,$

the last equation may also be written as,

(13) $$\frac{1}{V} = \frac{1}{V_1} + \frac{d_i \log \frac{1}{k}}{KC} + \frac{1}{KV}$$

from which it is apparent that if, for a constant inside diameter, d_i, of pyrometer tube, the thickness of the latter and therefore also K be varied, different values of V will be obtained. If now three such thicknesses were investigated, we should get three equations with three unknowns, V_1, V_2 and C, and these equations would be independent of each other. By solving these equations, the values of V_1, V_2 and C would be found as separate coefficients rather than their resultant value, V, which is the coefficient usually measured.

$A = V_d$

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V_1, V_2, C, is shown to be,

$$(11) \quad \frac{1}{A} = \frac{1}{A_1} + \frac{1}{A_2} + \frac{1}{A_g},$$

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Rewriting equation (11) with proper substitutions, we get,

$$(12) \quad \frac{1}{V \cdot d} = \frac{1}{V_1 \cdot d} + \frac{\log_e \frac{1}{K}}{C} + \frac{1}{V_2 \cdot Kd}$$

or

$$(12a) \quad \frac{1}{V} = \frac{1}{V_1} + \frac{d \log \frac{1}{K}}{C} + \frac{1}{KV_2}$$

Since,

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the last equation may also be written as,

$$(13) \quad \frac{1}{V} = \frac{1}{V_1} + \frac{d_1 \log \frac{1}{K}}{KC} + \frac{1}{KV_2}$$

from which it is apparent that if, for a constant inside diameter, d_1, of percolator tube, the thickness of the latter and therefore also K, be varied, different values of V will be obtained. If now three such thicknesses were investigated, we should get three equations, with three unknowns, V_1, V_2 and C, and these equations would be independent of each other. By solving these equations, the values of V_1, V_2 and C would be found as separate coefficients rather than their resultant value, V, which is the coefficient usually measured.

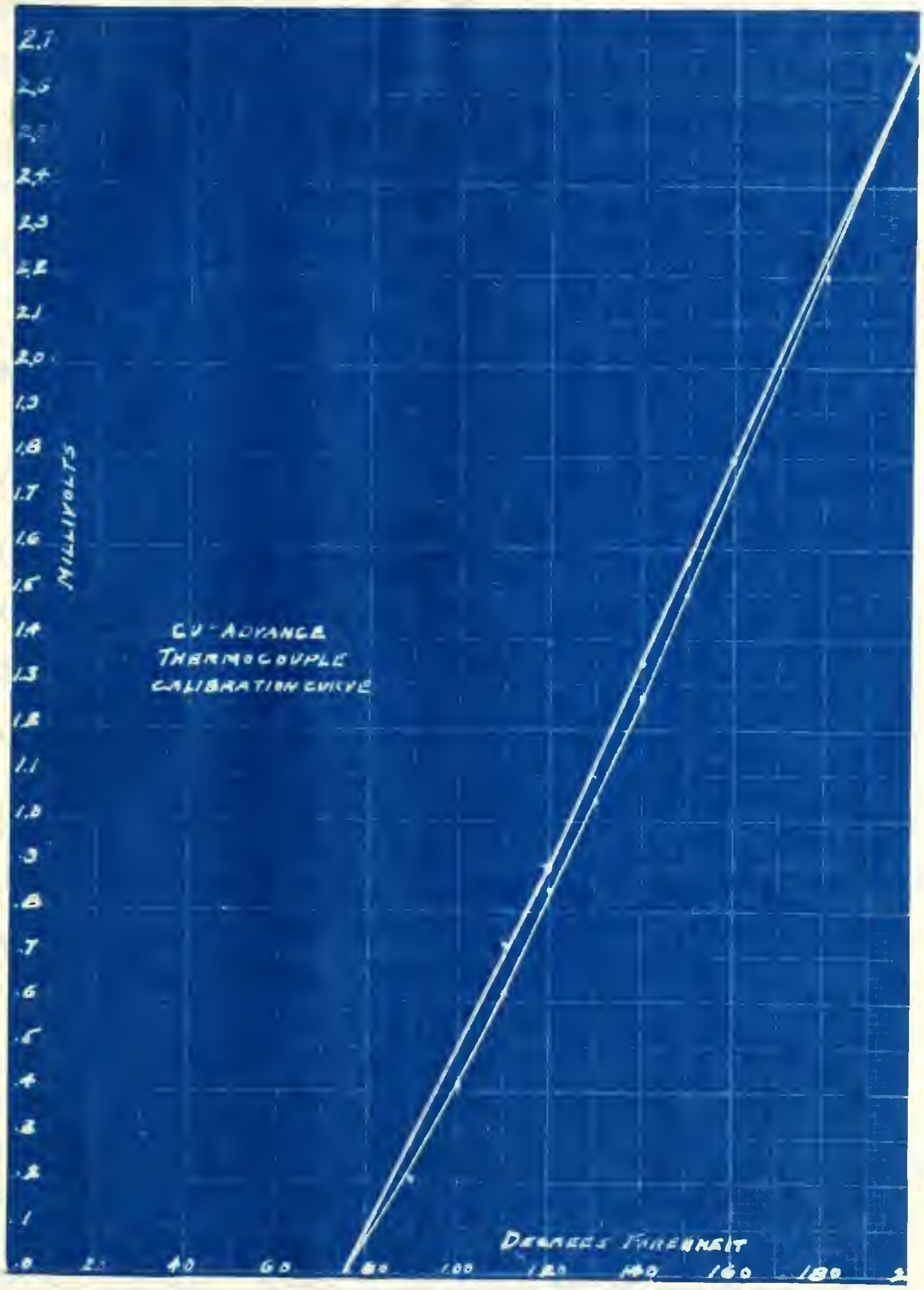
Then the value of $\underline{V}$ could be calculated , from eq. (13) for various thicknesses of tube, without the necessity of investigating each case experimentally. Also, knowing the effect of metal thickness upon the resultant coefficient of heat transmission, V, design [illegible] problems involving the thickness of pyrometer tubes could be analyzed and solved rationally.

Beside the mechanical problem of heat transmission involved in the electric furnace pyrpmeter design, there is the electrical problem of measuring and recording water temperature rise electrically.

Chart 5.

For indicating purposes, copper-advance thermocouples may be used. Their calibration curve is shown is Fig. 1.

Figure 1.



To increase the thermal e. m. f. a number of them may included in the same theperature plug and connected at their cold ends in series. Because of the small room occuppied by these thin thermocouples it would be no difficulty of placing as many as 10 to 20 of them in the same plug, and the temperature of water could be measured within. If now, one such plug is screwed into the cold end of the pyrometer tube and another one into the hot end of this tube, the difference between the two thermal e. m. f's. will be proportional to the difference of temperature between the hot and cold ends of the pyrometer tubes. This is evident if it is noted that the cold ends of the two thermocouples are at the same temperature, too. Then the emf's generated by the thermocouples are,

(14) $L_2 = K\,(t_2 - t_0)$

(15) $L_1 = K\,(t_1 - t_0)$

If now the difference between these two e. m. f's is measured by means of a differential millivoltmeter, the reading of the latter in millvolts will be proportional to the temperature difference, $t_2 - t_1$. Thus,

(16) $L_2 - L_1 = K\,(t_2 - t_1)$

The differential millivoltmeter may be calibrated to read, the difference between furnace and room temperature; or it may be calibrated to read o/o excess air directly.

Thus, for the first case, we combine equations (4a) and (16), and we get,

(17) $$t_g - t_w = \frac{387\, d_i v\, (t_2 - t_1)}{(1+n)\, VL} = \frac{387 d_i v}{K(1+n)VL}\left(L_2 - L_1\right) = K\,(L_2 - L_1)$$

Since the difference between the mean water temperature, t_w, in the pyrometer tube and the room temperature, t_o, is small as compared with the furnace temperature, tg, the above expression shows ~~the difference~~

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The differential millivoltmeter may be calibrated to read, the difference between furnace and room temperature; or it may be calibrated to read o/o excess air directly.

Thus, for the first case, we combine equations (16) and (11), and we get,

$$(17) \quad t_2-t_0 = \frac{387\,d_1v\,(t_2-t_1)}{(1+n)\,W_1} = \frac{387\,d_1v}{(1+n)\,W_1}(t_2-t_1) = K\,(t_2-t_1)$$

Since the difference between the cold water temperature, t_1, in the pyrometer tube and the room temperature, t_0, is small as compared with the furnace temperature, t_2, the above expression shows ~~the~~

that the millivoltmeter measures the difference between furnace and room temperatures directly.

For the second case, we note that the rise in temperature of the gases in the furnace above room temperature may be expressed by,

$$(18) \quad t_g - t_a = \frac{fH}{(W+1)C_p}$$

where,

H = Btu/# coal

W = # air /# coal

C_p = specific heat of air, at constant pressure

f = correction factor for radiation, incomplete combustion, etc.

Now, it is an accepted fact that for all coals, about 7.5 lbs. of air are required for each 10,000 Btu in the coal. Therefore, the theoretical air requirements, W_o, for H Btu or per lb. of coal is,

$$(19) \quad W_o = \frac{7.5\,H}{10,000}$$

If <u>n</u> times the theoretical requirements of air is used, then,

$$(20) \quad W = nW_o = \frac{7.5nH}{10,000}$$

and the temperature equation (18) may be rewritten as,

$$(21) \quad t_g - t_a = \frac{fH}{\left(\frac{7.5nH}{10,000} + 1\right) C_p} = \frac{f}{\left(\frac{7.5n}{10,000} + \frac{1}{H}\right) C_p}$$

Since, the expression $\frac{1}{H}$ is much smaller than $\frac{7.5n}{10,000}$, we may replace the former with the average value corresponding to H = 12,500 Btu./#, and we get,

$$(21a) \quad t_g - t_a = \frac{f}{\left(\frac{7.5n}{10,000} + .00008\right) C_p}$$

For any given furnace, the correction factor <u>f</u>, which depends mainly upon the direct rediation from the fire to the boiler, is a fixed

characteristic. Therefore, when f or rather the ratio of $\frac{f}{C_p}$ is once determined for a given boiler setting, the relation between furnace temperature difference, t_g-t_a, and o/o air, n, becomes fixed and definite, <u>regardless what the nature of coal or the flue gas analysis may be</u>.

Thus, for $f = .80$, $C_p = .24$, and theoretical air requirements or $n = 1$, we get,

$$t_g-t_a = \frac{.80}{(.00075+.00008)\ .24} = \underline{4000^\circ\ F}$$

For the same conditions and 200o/o air, or $n = 2$, we get,

$$t_g-t_a = \frac{.80}{(.00150+.00008)\ .24} = 2100^\circ\ F$$

which justifies the statement previously made that the furnace pyrometer indication is approximately <u>inversely</u> propertional to the o/o air used for combustion. The more exact relation is given by equation (21a). It is to be noted also, that if in the case of theoretical air requirements, the assumption of 12,000 Btu/# coal has an error of say 10%, then since .00008 is about 10% of .00075, a 10% error in the former results in only 10% of 10% or 1% in the sum of $\underline{.00075+.00008} = .00083$. For 100% excess air this error is reduced to ½ %, etc. Since the usual condition is 100% or more excess air, the approximation of $\frac{1}{H} = .00008$ is within permissible limits of error, and equation (21a) is justified.

Evidently then by combining equations (17) and (21a), we can get a direct relation between millivoltmeter readings, e_2-e_1 and % air, n, used in the furnace. Thus we have,

$$(22) \qquad t_g-t_w = \frac{387 d_i v\,(e_2-\epsilon_1)}{K\,(1+n)L} = t_g-t_a = \frac{f}{\left(\frac{7.5n}{10,000}+.00008\right) C_p}$$

or

$$(23)\quad n = \left[\frac{kf\,(1+n)\,\nabla L}{387 d_i\ v C_p\ (e_2 - e_1)} - .00008 \right] \frac{10,000}{7.5} =$$

$$= \frac{3.45\ kf\ (1+n) \nabla L}{d_i\ v\ C_p} \quad \frac{1}{e_2 - e_1} - .107 = \frac{K_2}{e_2 - e_1} - .107$$

where,

$$k2 = \frac{3.45Kf\ (1+n)\ \nabla L}{d_i\ v\ C_p}$$

By means of the last equation, the millivoltmeter may evidently be calibrated to read % air in furnace directly.

If the furnace temperature difference is to be recorder, the thermocouples are replaced by resistance coils of apprecialbe resistance temperature coefficient. Very thin enameled copper wire is best for the low temperatures (below 200° F) encountered in the water of the pyrometer tube. Thus, since,

$$(24)\quad R_1 = R_o \left[1 + a\ (t_1 - 32)\right]$$

$$(25)\quad R_2 = R_o \left[1 + a\ (t_2 - 32)\right]$$

where R_o = resistance of the wire at 32°F we have,

$$(26)\quad R_2 - R_1 = R_o\ a\ (t_2 - t_1)$$

Therefore, the water temperature rise may be calcualted by measuring the difference of resistance between two copper coils placed at the hot and cold ends of the pyrometer tube, respectively. The relation between the resistance difference, R_2-R1, and the furnace temperature difference is the same as that given by eq. (17) for thermocouples, if K is replaced by R_o a . The same holds true for the % air relation, as given by eq. (23).

To measure the difference of resistance, R_2-R_1, automatically, the differential galvanometer method is used. The galvanometer will read zero when sufficient balancing resistance is added in series with the smaller resistance, R_1, to balance the a larger resistance R_2, i. e.,

when the voltage across the first two resistances is equal to that across the last resistance. When due to change in temperature, the decrease or increase of resistances unbalances the voltages, the galvanometer will deflect in either direction depending upon the direction of unbalance.

If a galvanometer relay is used, similar r to the one used for flow measurement by the Sargen Steam Meter Co., then the deflection of the galvanometer may be caused to act like an automatic switch closing the field circuit of a series motor of the Universal type, and the motor will rotate in a direction corresponding to that of the galvanometer deflection. The motor may be made to move a rheostat handle and thus vary the balancing resistance $R = R_2 - R_1$ until the galvanometer returns to its zero position, the field of the motor is automatically opened by the galvanometer relay, and the motor is stopped.

The balancing resistance $R = R_2 - R_1$ may be calibrated to read directly either furnace temperature difference, $t_g - t_a$, or % excess air, n-1, as may be desired. The motor may be made to move a graphic pen a well as an indicating pointer, and thus the pyrometer may be made recording.

FURNACE PYROMETER CALIBRATION

The pyrometer described was tested on a 350 H. P. Sterling ~~bil~~ boiler at the Armour Institute. The water was supplied by a $\frac{3}{4}$" pipe line at city water pressure, the flow being regulated b y a ~~be~~ valve. A monometer at the cold end of the pyrometer tube indicated the pressure of the flowing water at the beginning of the tube, and when at the hot end, the water was allowed to discharge freely into the ~~swer~~ sewer at atmospheric pressure without any restricting valves, the monometer measured directly the friction pressure drop through the pyrometer tube. By actually weighing the water discharge, the

when the voltage across the first two resistances is equal to that across the last resistance. This due to change in temperature, or decrease or increase of resistance, unbalances the voltages, the galvanometer will deflect in either direction depending upon the direction of unbalance.

If a galvanometer relay is used, similar to the one used for flow measurement by the Rutgers Steam Meter Co., then the deflection of the galvanometer may be caused to act like an automatic switch closing the field circuit of a series motor of the universal type, and the motor will rotate in a direction corresponding to that of the galvanometer deflection. The motor may be made to move a rheostat handle and thus vary the balancing resistance $R = R_2 - r_1$ until the galvanometer returns to its zero position, the field of the motor is automatically opened by the galvanometer relay, and the motor is stopped.

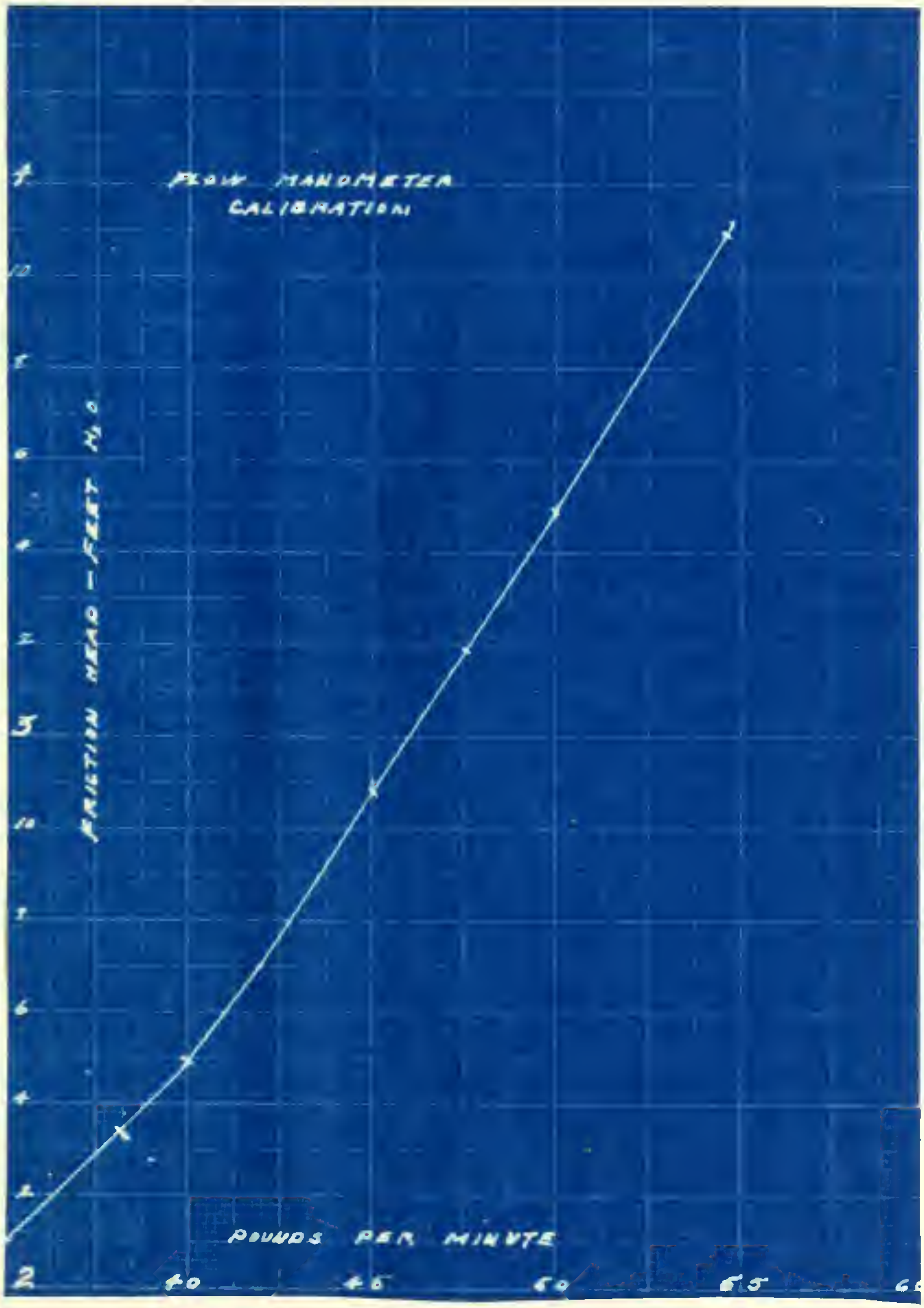
The balancing resistance $R = R_2 - r_1$ may be calibrated to read directly either surface temperature differences, $t_1 - t_2$, or a common aim, m-l, as may be desired. The motor may be made to move a pen as well as an indicating pointer, and thus the apparatus may be made recording.

PYROMETER CALIBRATION

The pyrometer testing was tested on a 500 H. P. Sterling bent boiler at the Armour Institute. The water was supplied by a 2" pipe line at city water pressure, the flow being regulated by a valve. A manometer at the cold end of the pyrometer tube indicated the pressure of the flowing water at the beginning of the tube, and that at the hot end, the water was allowed to discharge freely into the sewer at atmospheric pressure without any obstruction whatever, the manometer measured directly the friction pressure drop through the pyrometer tube. By actually weighing the water discharged, the

monometer may be calibrated to read lbs. of water per minute, directly. The monometer calibration curve, is shown in Fig. 2, below.

Figure 2.



By setting the valve until the monometer indicated corresponded to the desired flow, the latter could be maintained constant during each run.

Specially made temperature cups were screwed into ~~a~~ Y— fittings , once at the cold and another at the hot end of the pyrometer tube. These cups were partially filled with oil, and calibrated mercury thermometers were immersed into this oil. These thermometers gave the cold and hot end temperatures of the water flowing through the pyrometer tubes.

For measuring the furnace temperatures at the different points of the bridge wall, a thermocouple twelve feetlong was obtained and marked every foot of its length. Also a small fire door between the bridge wall and the first row of boiler tubes was opened and an asbestos board with an opening on its bottom was fitted into the door cavity. The ~~out~~- thermocouple could then be moved in and out the furnace through the opening of the asbestos board, without the objection of letting a lot of cold air into the furnace.

The thermocouple was connected to a Leeds & Northrop potentiometer type of millivoltmeter, the thermal e. m. f. being ~~bing~~ balanced against the voltage drop across a variable calibrated resistance, produced by the e. m. f. of a standard cell. When the voltages were balanced, the thermal e. m. f. was disconnected, and the drop across the variable resistance was measured by the millivoltimeter. In that way, the error due to the voltage drops across the connecting wires were avoided.

The test consisted of adjusting the flow to a predetermined constant value by means of the valve and the monometer; of inserting the thermocouple to the last marked foot, and taking the temperature reading by means of the millivoltimeter; and finally, of reading the two mercury thermometers in the cold and hot end temperature cups.

The thermocouple would then be moved out to next foot mark, and the readings would be repeated. This was done for eight different foot marks, corresponding to almost every foot along the bridge wall.

A series of such tests were made on different days in order to cover as large a range of furnace temperature as possible.

A preliminary calibration test of the thermocouple was made in an electric furnace against a standard platinum thermocouple.

RESULTS AND CALCULATIONS

The calibration curve of the 12 foot thermocouple is shown in Figure 3. As shown by the curve, the calibration was made up to 2200° F.

FIGURE 3.

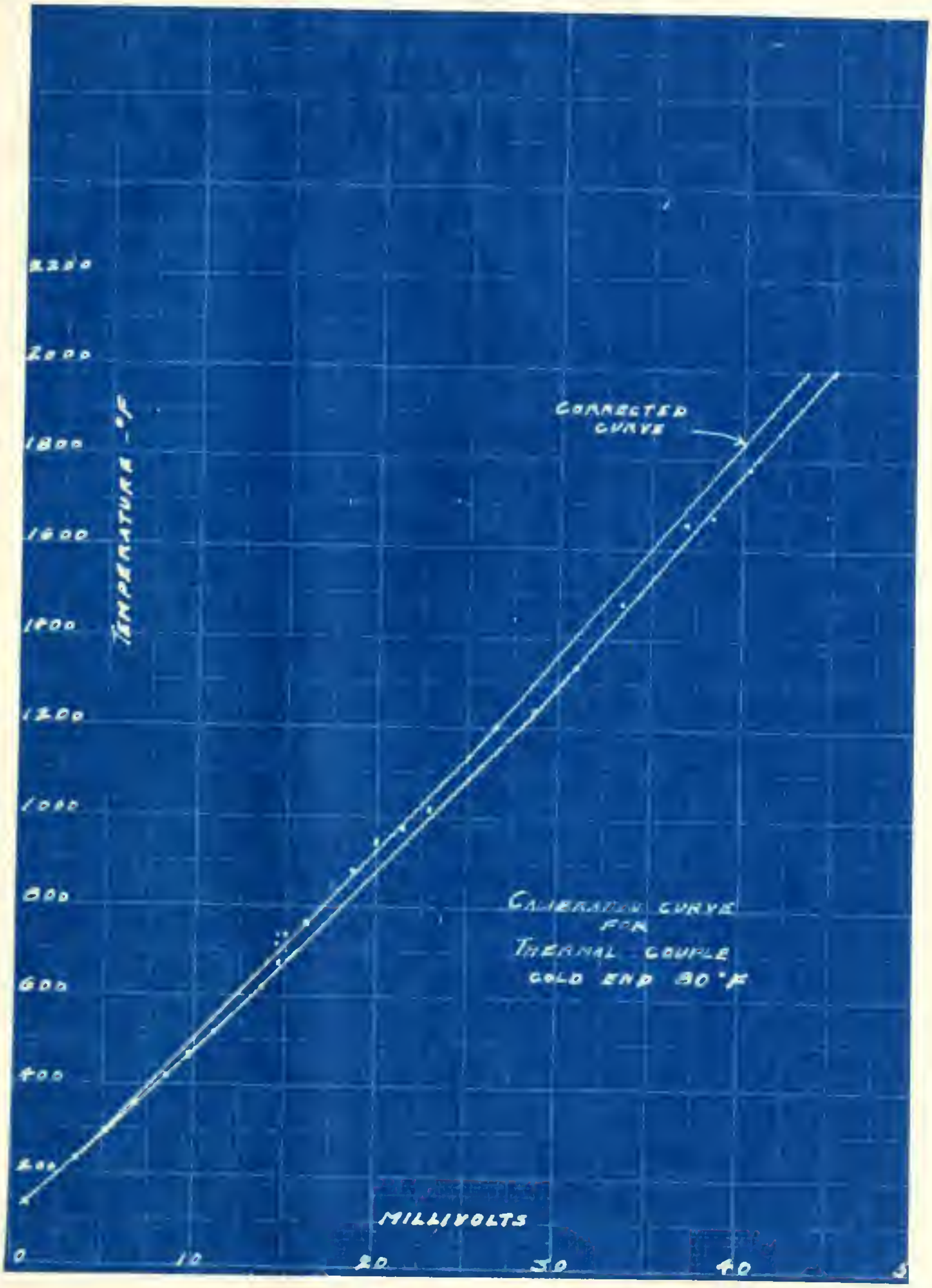

TEMPERATURE - °F
2200
2000
1800
1600
1400
1200
1000
800
600
400
200
0
10
20
30
40
MILLIVOLTS
CORRECTED CURVE
CALIBRATION CURVE FOR THERMAL COUPLE COLD END 80° F

Table 1 gives a sample of data taken for the furnace temperature distribution and heat transmission tests. From the millivoltmeter readings and the thermocouple calibration curve, the furnace temperatures were figured out at different points of the bridge wall.

TABLE 1.

SAMPLE DATA SHEET

Point	MILLIVOLTS	Furnace Temp.	Cold end Temp.	Hot end Temp.	Temp difference
2	26.7	1210	44	114	70
3	39.1	1775	"	108.6	64.5
4	47.4	2160	"	113	69
5	41.7	1900	"	113	69
6	41	1865	"	115	71
7	38	1726	"	113	69
8	39.4	1790	"	113	69
9	41	1865	"	113	69

Because of the variation of average furnace temperature during any one test, it was necessary to take the readings for the conditions as found and then tabulate them according to water temperature rises porduces. Thus all readings corresponding to within $2\frac{1}{2}^{o}$ F on either side of say 40^{o} F rise were tabulated together, and the furnace temperatures for the different points along the bridge wall for this average condition were thus available for comparison. Naturally, the tables for some such water temperature rises were more complete than for others, and special efforts were then made to secure the readings at the points and for the water temperatures for which one was short of data. The highest water temperature rises investigated were around the 90^{o} F point.

A sample of such tabulated data as well as the averages of the furnace and water temperatures is given in Table 2. The latter also includes the calculated U for the particular furnace temperature difference under consideration.

TABLE 2.

Because of the variation of furnace (?) temperature during
-ing one test, it was necessary to take the readings for the conditions as found and then tabulate them according to water temperature rises obtained. Thus all readings corresponding to within $2\frac{1}{2}^{\circ}$ F on either side of any 400 F rise were tabulated together, and the furnace temperatures for the different points along the bridge wall for this average condition were then available for comparison. Naturally, the tables for some such water temperature rises were more complete than for others, and special efforts were then made to secure the readings at the points and for the water temperatures for which one was short of data. The highest water temperature rises investigated were around the 500 F point.

A sample of such tabulated data as well as the averages of the furnace and water temperatures is given in Table . The latter also includes the calculated q for the particular furnace temperature distance under consideration.

r 1		r 2		r 3		r 4		r 5		r 6		r 7		r 8		r 9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1310	67	1360	63	1440	66	1780	64.5	1700	64.6	1845	66.6	1815	64	1015	66	1790	63.5
1325	64.5	1325	67	1580	66	1625	64.5	1685	67.	1640	66.6	1810	65	1806	67	1795	64
				1620	62.5	1700	66.5	1735	63	1800	63	1650	66.6	1870	64	1765	67
				1720	67			1715	64.5	1805	66			1800	65	1740	66.5
1304	65.75	1342	66.	1605	63.6												
				1593	65.6	1702	64.8	1710	64.75	1772	66.2	1792	64.8	1825	66.5	1797	66.3

Average T = 1634
" d = 66.11
" U = 22.45

It will be noted that for any given bridge wall point of this table the furnace temperature varies as much as 5% above the average temperature at this point. This indicates the variation of the temperature distribution along the bridge wall with time. If the variations at all points along the bridge wall were all in the same direction or non compensating, there would be a maximum possible, sampling error of 5%. Ordinarily there would be some compensation, so that the variation of the relation between the average furnace temperature and the average water temperature rise would be less than 5%. However, ~~as~~ to play safe, we may state that as efficient as about 10' of tube along the bridge wall may be for sampling purposes as compared with that of point sampling, ~~for~~ there is still a maximum possible error of 5% due to the variation of bridge wall temperature distribution.

It may now be in order to remark that the pyrometer tube ~~to~~ was slightly covered with sooth or slag, most of which was usually carried away by the moving gases. Several attempts were made to note the variation of the results, if the materials on the pyrometer tube were scraped off. It was found that there was about 1% increase in conductivity, when the tubes were thus treated. Considering the 5% possible error in the sampling effieiency of the tube, it is evident that the effect of sooth accumulation outside the tube is negligible.

The average temperature distribution curves along the bridge wall for several water temperature rises are plotted in Fig. 4 below.

It will be noted that for any given bridge wall point on this table the furnace temperature varies as much as 5% above the average temperature at this point. This indicates the variation of the temperature distribution along the bridge wall with time. If the variations at all points along the bridge wall were all in the same direction or non compensating, there would be a maximum possible sampling error of 5%. Ordinarily there would be some compensation, so that the variation of the relation between the average furnace temperature and the average water temperature rise would be <u>less</u> than 5%. However, ~~as~~ to play safe, we may state that as efficient as about <u>10' of tube</u> along the bridge wall may be for sampling purposes as compared with that of <u>point</u> sampling, ~~for~~ there is still a maximum possible error of 5% due to the variation of bridge wall temperature distribution.

It may now be in order to remark that the pyrometer tube was slightly covered with soot or slag, most of which was usually carried away by the moving gases. Several attempts were made to note the variation of the results, if the materials on the pyrometer tube were scraped off. It was found that there was about 1% increase in conductivity, when the tubes were thus treated. Considering the 5% possible error in the sampling efficiency of the tube, it is evident that the effect of soot accumulation outside the tube is negligible.

The average temperature distribution curves along the bridge wall for several water temperature rises are plotted in Fig. 4 below.

FIGURE 4.

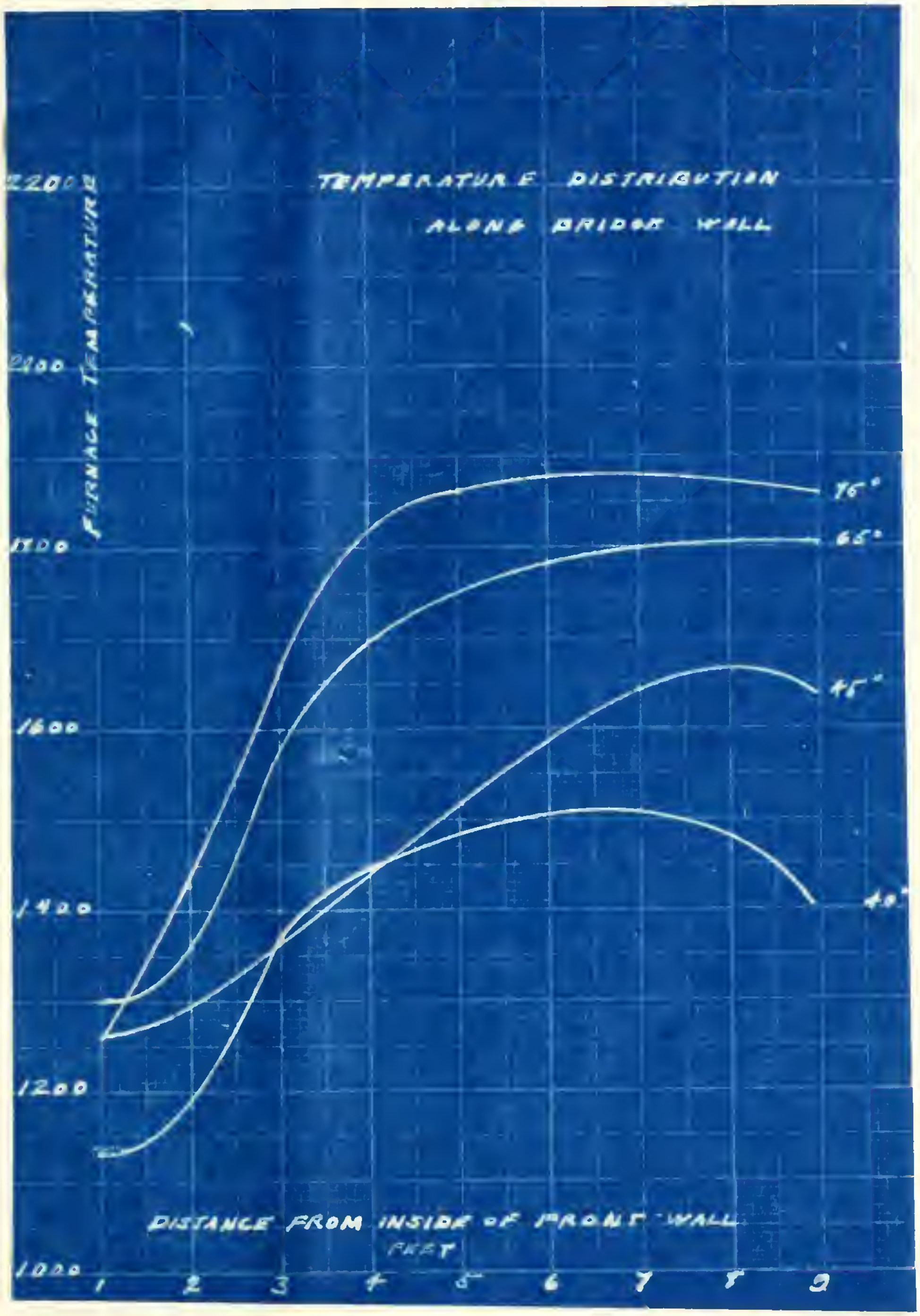
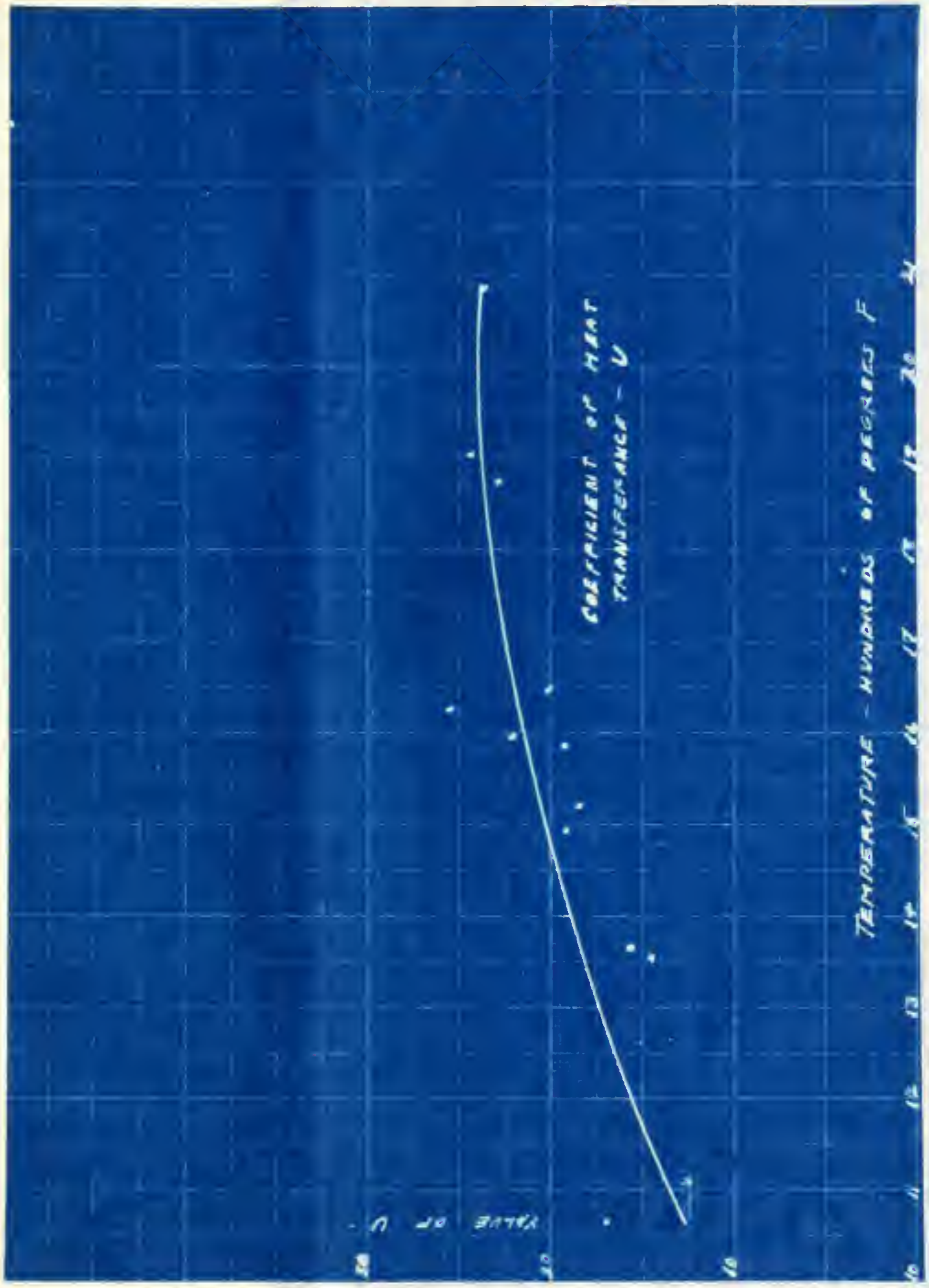

TEMPERATURE DISTRIBUTION
ALONG BRIDGE WALL
FURNACE TEMPERATURE
1200
1400
1600
1200
1000
75°
65°
45°
40°
DISTANCE FROM INSIDE OF FRONT WALL
FEET
1
2
3
4
5
6
7
8
9

Figure 5 gives the U- curve or the values of U calculated for different furnace temperature differences, from the tables given in the appendix and similar to table 2.

From the curve values of U could be found for any furnace temperature differences, $t_g - t_a$, and used for calibrating the indicating or recording pyrometer to read furnace temperature differences directly.

After a comparison is made between these values of U and those between these ~~valu~~ that will be obtained from the heat transmission test using an electric furnace, it is hoped that a rational relation between U and overall temperature difference will be evolved.

FIGURE 5.


COEFFICIENT OF HEAT
TRANSFERANCE - U
TEMPERATURE - HUNDREDS OF DEGREES F
VALUE OF U

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
						1800	89	1980	91	2160	91	2120	88.6	2155	92.5	2035	88.6
												2060	92				

Average T = 2085
" d = 91.74
" U = 23.8

/	1	r	2	r	3	r	4	r	5	r	6	r	7	r	8	r	9
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
		935	26	1025	27			1175	26			1245	26				
				1125	27			1270	26								

Average T = 1119
" d = 26.25
" V = 13.27

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
95.6	30															1275	27

Average T. 1065
" d 29
" V 16.47

	1		2		3		4		5		6		7		8		9	
	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
		1045	34										1350	33	1515	37	1540	37
													1446	35	1435	37.6	1500	37

Average T = 1367
" d = 35.66
" V = 14.57

1 2 3 4 5 6 7 8 0

T d T d T d T d T d T d T d T d T d

1105 38 1175 38 1400 38

1130 40.5

1500 42 1515 41 1466 39

1516 39

Average T: 1365

" d 39.16

" U 15.94

r 1		r 2		r 3		r 4		r 5		r 6		r 7		r 8		r 9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1380	44	1450	46	1655	—	1380	44	1670	47	1435	46.5	1645	47			1640	47.5
1140	47.6	1410	47.5			1670	47	1515	46								
						1375	45	1690	46.5								
						1405	45										

Average T: 1493
" d: 46.1
" V: 10.05

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1830	52.5	1360	52	1525	48	1480	49.5	1575	49	1715	51	1705	52.5	1670	52.5	1620	49
				1400	48	1430	52.5	1640	52			1520	47.5	1590	48	1520	47.5
				1380	51.5	1595	52.5	1535	51.5					1520	49.5		
														1585	48.0		

Average $T = 1561$

" $d = 50.72$

" $V = 17.46$

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1255	55	1105	56.6	1610	57.5	1610	55	1725	53.5	1735	55	1795	56	1580	55	1690	56.5
				1530	57.5	1600	56.5	1655	57.5	1670	54					1695	56.5
1230	53									1645	55					1640	51.0
				1520	57.5	1605	55.75	1690	55.5	1735	57						

Average T = 1674
" d = 55.54
" V = 10.27

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1230	60.5	1295	62	1625	60	1725	60	1715	57			1815	57.5	1965	61	1705	62
1270	61.5	1340	53.5			1700	62	1770	58.5	1775	58	1775	61	1800	61.5	1820	62
1275	57.5	1390	57					1695	62	1665	61	1655	59.5	1735	57.5	1645	60.5
		1300	59							1620	61.5			1605	50.5		
1262	59.8	1339	55.6			1712	61	1760	60.6	1710	60.5	1772	60.7	1705	61		
														1715	61		

Average T = 1693
" d = 60.26
" V = 80.5

r 1		r 2		r 3		r 4		r 5		r 6		r 7		r 8		r 9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1310	67	1360	63	1440	66	1770	64.5	1700	64.6	1845	66.5	1815	64	1015	66	1790	63.5
1325	64.5	1326	67	1650	66	1625	64.6	1685	67.	1640	66.6	1810	66	1806	67	1796	64
				1620	62.6	1700	66.5	1737	63	1700	63	1650	66.6	1880	64	1765	67
				1720	64			1716	64.6	1806	66			1700	65	1740	66.5
1304	65.75	1342	66.	1605	63.6												
				1593	66.0	1702	64.8	1710	64.75	1772	66.2	1792	64.8	1825	66.5	1797	66.3

Average T = 1694

" d = 66.11

" U = 22.45

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1520	68.5					1655	72	1800	68.5	1680	68.5	1865	71.5	1785	70		
1570	70.5	1500	69	1665	67.5	1590	71.5	1700	67.5	1710	68.5	1740	68	1745	69.5	1975	69.5
1315	69.5	1330	69.5	1630	71.5	1640	69.5	1790	70	1925	69.5	1755	69	1895	71	2035	71
		1575	67.5	1715	72	1765	70.5			1970	71	1795	69	1920	70	2060	68

Average T = 1694
" d 69.57
" V 2242

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1370	76.5	1420	75	1560	77	1630	76	1955	77	1595	72.5					1840	76
		1420	75	1780	76			1820	74								
								1815	73								

Average $T = 1624$
" $d = 74.69$
" $V = 25.72.$

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1555	77.6	1606	77.6	1810	80.6	1815	78			2130	81	2000	78	2015	78	2275	81
1545	81																		

Average T = 1873
" d = 79.15
" V = 22.98

1		2		3		4		5		6		7		8		9	
T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d	T	d
1380	84.5			2020	86							2160	86				
1670	84																

Average T = 1001
" d = 85.41
" U = 24.4